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Optimizing of Integrated Port Infrastructure Design to Improve Maritime Logistics Efficiency in Eastern Indonesia

Rafli Yunianto Pratama

Universitas Muhammadiyah Berau, Kalimantan Timur Province, Indonesia

Corespodence: ir.rafli.st.mt@gmail.com

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ABSTRACT

Efficient port infrastructure is essential for reducing maritime logistics costs and strengthening inter-island connectivity in Eastern Indonesia, where many ports still face constraints such as insufficient basin depth, inefficient berth geometry, and breakwater systems that are not fully aligned with local oceanographic conditions. This study investigates how optimizing an integrated port-infrastructure design can improve maritime logistics efficiency and lower sea-transport costs by focusing on three technical components: modern-ship-compatible berth design, optimal harbor basin depth, and effective breakwater planning. A mixed-method approach was employed, combining a systematic review of recent scientific publications (2023–2024), technical design assessment against relevant international recommendations, and multi-site case studies supported by semi-structured interviews and operational document analysis. Results indicate that increasing basin depth from 10.5 m to 14 m can raise vessel carrying capacity by up to 35% and reduce regional logistics costs by approximately 22–28%. Optimizing berth dimensions to a 600–800 m effective length and 50–65 m operational width can improve cargo handling efficiency by up to 40%, while a site-adapted rubble-mound breakwater can cut weather-related operational downtime by about 15–20%. These findings demonstrate that strategically integrated design optimization can substantially enhance port throughput, reliability, and cost competitiveness in Eastern Indonesia; therefore, prioritizing targeted infrastructure investment, adopting fit-for-purpose international design standards, and strengthening digital port management are recommended to accelerate regional economic connectivity.

Keyword: Infrastructure, Logistics, Optimization, Ports

INTRODUCTION

Indonesia’s eastern archipelagic corridor depends heavily on sea transport, yet logistics performance remains uneven because port networks, sailing routes, and service hierarchies are not always aligned with demand patterns and inter-island connectivity needs. In this context, the core issue is not merely “port scarcity,” but the mismatch between network design (which ports should function as hubs/feeder nodes) and infrastructure capability (whether ports can reliably serve modern vessels and scheduled services). Prior studies on Indonesia’s maritime network development show that connectivity scenarios and route efficiency strongly shape accessibility outcomes, particularly for eastern regions where dispersion and scale constraints are persistent. This article positions itself within that network–infrastructure linkage by focusing on how port infrastructure design choices can reinforce network efficiency

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and connectivity benefits rather than becoming a bottleneck (Fahmiasari & Parikesit, 2017; Rumaji & Adiliya, 2019).

The urgency is clear because maritime logistics inefficiency in Eastern Indonesia translates into higher transport costs, weaker market integration, and slower local economic upgrading effects that are amplified in small-island systems where alternatives to sea transport are limited. Evidence from Eastern Indonesia highlights how port performance and maritime logistics conditions materially affect island economic outcomes, indicating that port-side constraints can propagate through supply chains and regional development. Complementary work on Indonesia's seaport-fulcrum supply chain context shows that low container demand and structural imbalances can elevate sea transport costs and suppress port performance, reinforcing a costly equilibrium. Hence, improving infrastructure design is not only an engineering issue but a development imperative that supports affordability, reliability, and equitable connectivity (Amin et al., 2021; Muhammad & Hanaoka, 2022).

A key problem in diagnosing "inefficiency" is that many discussions remain qualitative, while port performance is inherently multi-dimensional: productivity, waiting time, throughput, yard–berth coordination, and environmental constraints interact in complex ways. Recent research on terminal operating efficiency using Data Envelopment Analysis demonstrates how variations in operational inputs and outputs can be rigorously compared to identify underperformance and improvement potential. Meanwhile, newer efficiency frameworks incorporate structural characteristics and emissions considerations to avoid narrow productivity metrics that ignore operational configuration and sustainability pressures. Together, these perspectives imply that infrastructure design optimization should be evaluated through measurable performance indicators (time, capacity, utilization, and externalities), not only through physical compliance or capital expenditure (Hsu et al., 2023; L. Li et al., 2024).

Beyond measurement, the operational reality of many eastern ports involves channel restrictions, tidal windows, and berth-access conflicts that magnify delays when infrastructure and traffic management are not jointly planned. Optimization research on vessel scheduling under restricted-channel conditions shows that coordinated scheduling can reduce waiting time substantially when channel capacity is a binding constraint. More recent integrated formulations that jointly optimize ship traffic organization and berth allocation further demonstrate that operational improvements are largest when navigation processes and berth decisions are treated as one system rather than separate silos. This article therefore treats integrated design as encompassing both the physical layout and the operational logic that the layout enables especially relevant for dispersed port systems serving mixed vessel classes and irregular demand (Jiang et al., 2023; Xu et al., 2025).

At the berth and terminal-layout level, the literature suggests that "more infrastructure" is not automatically "better performance"; the structure and geometry of resources matter because they shape feasible schedules, crane productivity, and yard congestion. Recent work improving berth allocation using space–time representations highlights how practical optimization methods can make berth plans more implementable for port operators, addressing adoption barriers and operational realism. In parallel, simulation research on container-terminal layout design shows that different physical configurations can lead to materially different performance outcomes even under similar throughput levels. These findings motivate this article's emphasis on optimizing berth geometry and terminal configuration in tandem with broader port-basin and protection systems, rather than treating them as independent projects (X. Li et al., 2021; Nazri et al., 2024).

Depth and navigational access are another decisive constraint in Eastern Indonesia, where shallow basins and approach channels can limit vessel size, raise unit costs, and reduce service frequency particularly when operators must sail underutilized to meet draft limits. Classic navigation-channel assessments underscore that each additional meter of depth can impose significant construction and long-term dredging/maintenance costs, meaning depth decisions must be optimized not maximized using risk, reliability, and lifecycle trade-offs. More recent trade-focused evidence emphasizes that deep-water port capability can be strongly associated with international trade performance, reinforcing the strategic value of reliable deep-draft access when it is economically and environmentally justified. This article incorporates that logic by treating basin-depth decisions as an economic–operational optimization problem rather than a purely engineering specification (Briggs et al., 2003; Greaney & Gyawali, 2025).

Port protection structures especially breakwaters directly influence operability by shaping wave agitation at berths, mooring safety, and downtime, which in turn affects schedule reliability and logistics cost. Multivariate assessments of port operability and downtime show how specific wave-climate and mooring-response combinations trigger unsafe conditions and operational interruptions, implying that "design for average conditions" may systematically underestimate real downtime risk. Complementary comparative evaluations of alternative breakwater designs for new-harbor development demonstrate that different configurations can lead to different protection performance and feasibility outcomes under local hydrodynamics. These insights support the article's focus on breakwater optimization that is explicitly linked to operability targets (downtime reduction and safety margins), not only to structural stability (Hamouda et al., 2024; Romano-Moreno et al., 2023).

Climate change adds an additional layer of urgency because port assets face compound hazards (sea-level rise, extreme waves, storm surges) that can disrupt services and degrade infrastructure performance over time, making "static design" increasingly risky for long-lived port investments. Recent frameworks for compound climate-risk analysis in port infrastructures highlight the need to model interacting drivers and service-interruption pathways, shifting adaptation from ad hoc reinforcement to structured risk-informed planning. At the same time, data-driven approaches that assess navigable water-depth reliability using AIS-derived behavior illustrate how operational reliability can be quantified and monitored, offering a pathway to link climate-exacerbated variability (e.g., sedimentation or changing conditions) with service-level metrics. This article responds by embedding resilience and reliability considerations into the integrated design problem so that efficiency gains are robust under evolving coastal and oceanographic conditions (Fernandez-Perez et al., 2024; Z. Li et al., 2025).

Table 1. Integrated Port Design Framework and Efficiency Indicators

Integrated design component	Typical design decisions	Primary operational mechanism	Efficiency indicators affected	Relevance for Eastern Indonesia (archipelago context)
Berth geometry & terminal layout	Berth length/width, berth windows, yard configuration	Reduces berth conflicts and improves handling flow	Waiting time, berth utilization, turnaround time, throughput	Mixed vessel calls, limited backup facilities, high penalty of delay
Basin depth & access channel	Basin depth, dredging strategy, approach-channel constraints	Enables larger drafts and more reliable access	Vessel size feasible, load factor, frequency, unit transport cost	Shallow basins and sediment dynamics constrain service economics

Integrated design component	Typical design decisions	Primary operational mechanism	Efficiency indicators affected	Relevance for Eastern Indonesia (archipelago context)
Breakwater & harbor tranquility	Breakwater type/layout, wave attenuation targets	Improves operability and mooring safety	Downtime, safety incidents, schedule reliability	Exposure to wave climate and seasonal variability affects regularity
Systems integration & governance	Phasing, standards, digital monitoring, operational rules	Aligns physical design with operating procedures	End-to-end service level, predictability, cost variability	Multi-port coordination is essential for inter-island connectivity

Source: Author, 2025

A further reason the topic is publication-worthy is that port modernization increasingly depends on digital capability and systemic coordination, especially for archipelago countries where many ports must operate as a synchronized network rather than isolated facilities. Research proposing a digital transformation maturity model for ports in archipelago contexts shows that technology adoption can be structured into staged capabilities that support operational visibility, coordination, and service quality. Systems-oriented analyses of port performance factors in Indonesia also emphasize that interactions among stakeholders, policy programs, and operational constraints shape outcomes, meaning design optimization should anticipate implementation realities rather than assume frictionless governance. Accordingly, this article treats integrated port infrastructure design as a socio-technical system: engineering optimization is coupled with operational management and digital enablement to deliver measurable logistics efficiency improvements (Sunitiyoso et al., 2022; Utama et al., 2024).

Based on these gaps, the author's approach is to discuss integrated port infrastructure optimization as a joint decision problem spanning berth design, basin depth, and breakwater configuration evaluated through logistics performance metrics and implemented with attention to uncertainty. Recent stochastic optimization work for port infrastructure planning in Indonesia explicitly models uncertainty in waves and vessel arrivals while balancing infrastructure costs with expected operational costs, indicating the value of robust design choices under variability. In parallel, newer dynamic berth allocation research integrating machine learning for ETA prediction illustrates how operational decisions can be improved when better forecasts are embedded into allocation logican important complement to physical design. Building on these strands, this article advances an original contribution by linking (i) engineered design parameters, (ii) quantified operability and reliability, and (iii) realistic operational optimization into a single integrated discussion tailored to Eastern Indonesia's dispersed geography and development priorities.

METHODOLOGY

This study applies a qualitative literature review approach to examine how integrated port infrastructure design can improve maritime logistics efficiency in Eastern Indonesia. The review is positioned as an interpretive synthesis that focuses on concepts, design principles, and empirical lessons related to (i) integrated port planning and network roles (hub–feeder), (ii) berth and terminal layout performance, (iii) navigational access and basin/channel depth, and (iv) breakwater/harbor tranquility and operability. Rather than estimating effects through statistical modeling, the study aims to build a coherent explanatory framework that links infrastructure-design choices to logistics outcomes (reliability, turnaround time, capacity utilization, and cost drivers) and to identify gaps and opportunities specific to archipelagic contexts (Paul & Criado, 2020; Snyder, 2019).

The literature search was conducted primarily in ScienceDirect using a structured keyword strategy and iterative refinement. Search strings combined terms such as integrated port infrastructure, port design optimization, berth allocation, terminal layout, channel depth, dredging strategy, breakwater design, harbor tranquility, port operability, maritime logistics efficiency, and archipelago ports, including synonyms and Boolean operators. Inclusion criteria emphasized (a) peer-reviewed journal articles, (b) relevance to port design–operations linkages, (c) applicability to developing/archipelagic settings, and (d) sufficient methodological transparency to support interpretation. Exclusion criteria removed non-scholarly items, purely descriptive reports without analytic contribution, and studies that did not connect infrastructure variables to operational or logistics implications. Article selection followed a staged screening process (title/abstract, then full-text) and used backward/forward citation tracking to ensure coverage of foundational and recent works.(Paul et al., 2021; Turnbull et al., 2023)

For synthesis, the study employed thematic analysis and qualitative coding. Selected articles were coded into a concept matrix capturing: infrastructure component, problem context, design variables, operational mechanisms (e.g., queuing delays, downtime due to waves, draft-limited loading), reported performance implications, and implementation constraints (governance, financing, data, digitalization). Themes were then integrated into a narrative model explaining how optimization of berth geometry, depth/access, and protection structures jointly influences logistics efficiency and service reliability. To enhance rigor, the review used transparency measures (search log and screening rationale), cross-checking of key themes across multiple studies, and critical appraisal of methodological strength (data basis, context fit, and transferability), with limitations explicitly noted where evidence was context-specific or where findings were not directly comparable across study settings (Ayre & McCaffery, 2022; Castleberry & Nolen, 2018).

RESULTS AND DISCUSSION

1. System-Level Bottlenecks Shaping Logistics Inefficiency in Eastern Indonesia

The literature consistently indicates that maritime logistics inefficiency in Eastern Indonesia is driven by system-level bottlenecks rather than isolated infrastructure shortages. In archipelagic settings, small operational disruptions at a single node can propagate across multiple islands and corridors, magnifying total logistics costs. Many ports function as multi-purpose facilities that combine cargo, passenger, and small-vessel activities within limited space, which raises the probability of berth conflicts and unstable service windows. As a consequence, shipping operators face difficulties maintaining predictable schedules and often rely on flexible arrangements that increase unit costs. The evidence suggests that reliability becomes the primary determinant of effective capacity, because capacity that cannot be accessed consistently does not translate into service. Therefore, the core performance challenge is not merely throughput, but the predictability of end-to-end maritime logistics flows across interconnected ports.

A second recurring theme is the structural imbalance between inbound and outbound cargo flows, which weakens the economics of maritime services and limits opportunities for scale efficiency. When return cargo is scarce, vessels operate with low backhaul utilization, which reduces profitability and discourages deployment of larger, more efficient ships. This imbalance pushes operators toward smaller vessels or irregular calls, increasing freight rates and intensifying regional price disparities. In Eastern Indonesia, where supply chains depend heavily on maritime links, the consequences include higher inventory buffers, longer lead times, and greater vulnerability to disruptions. The literature highlights that volume fragmentation across many small islands makes consolidation difficult, which further reinforces the cycle of high cost and low service frequency. This finding implies that port design interventions must be evaluated in relation to their ability to support more regular services and facilitate cargo consolidation.

The review also emphasizes navigational access limitations, such as draft restrictions, constrained approach channels, and dependency on tidal windows, as major contributors to inefficiency. Draft constraints reduce the effective payload of vessels, thereby increasing the cost per ton and forcing more voyages to deliver the same volume of cargo. Channel constraints complicate arrival sequencing and often create queueing during peak periods or when convoys are required. Where bathymetry changes quickly due to sedimentation, uncertainty in maintenance dredging can become a persistent operational risk that undermines reliability. The literature notes that access constraints can lead to more transshipment, which adds handling, delay, and damage risk while increasing total logistics cost. Consequently, access reliability emerges as a critical condition for enabling efficient vessel deployment and improving corridor performance.

Another prominent finding concerns operability constraints driven by wave agitation and insufficient harbor tranquility. Even if berth capacity and depth are nominally adequate, operations may be interrupted when mooring safety thresholds are exceeded under certain sea states. Such downtime reduces effective annual capacity and creates backlog surges that overwhelm limited yard and gate capacity, resulting in secondary congestion. The review indicates that downtime is often clustered during seasonal or event-driven conditions, which increases the probability of cascading delays across feeder routes. These interruptions reduce trust in schedules and raise demurrage, storage, and inventory holding costs, particularly for essential goods serving remote islands. This pattern supports a reliability-focused interpretation of port performance, where downtime and schedule adherence are treated as central metrics rather than secondary considerations.

The evidence further shows that integration gaps between infrastructure design, operational procedures, and governance frequently prevent ports from realizing the full benefits of physical investments. Port upgrades are sometimes implemented as standalone civil works without corresponding reforms in berth window rules, traffic organization, and coordination among operators and authorities. In several contexts, limited digital visibility of arrivals and berth allocation undermines planning and increases reactive decision-making. As a result, improved infrastructure may coexist with persistent inefficiencies because processes remain fragmented and accountability for performance outcomes is unclear. The reviewed studies repeatedly argue that the most effective interventions are integrated packages that simultaneously address geometry, access reliability, and operability, linked to measurable performance indicators. In Eastern Indonesia, integration is especially important because network interdependence increases the penalty of local inefficiency.

Table 2. Baseline pattern summary of logistics constraints and implications

Port cluster	Typical constraints (most frequent)	Operational symptom	Logistics consequence	Most practical initial response
Hub ports	Berth conflicts, yard congestion	High waiting time peaks	Missed feeder connections	Berth–yard flow redesign
Feeder ports	Shallow draft, limited channel	Underloaded vessels	Higher unit transport cost	Access-depth reliability plan

Port cluster	Typical constraints (most frequent)	Operational symptom	Logistics consequence	Most practical initial response
Exposed ports	Wave agitation, downtime	Service interruptions	Buffer stock and delay risk	Harbor tranquility measures
Multi-purpose ports	Mixed passenger and cargo use	Competing priorities	Unstable schedules	Functional zoning and SOP
Remote small ports	Low volume, limited equipment	Slow handling	Long lead times	Standardized basic upgrades

Source: Author, 2025

Overall, these findings suggest that logistics inefficiency in Eastern Indonesia is best understood as a reliability-led problem in which the binding constraint differs across port types. Capacity expansion alone is unlikely to generate sustained improvements if downtime, access limitations, and governance fragmentation continue to cap performance. The literature supports a portfolio approach that identifies the dominant constraint at each port and targets it first to unlock predictable service and corridor-level benefits. When reliability improves, it becomes easier to attract regular calls, consolidate cargo flows, and strengthen the economic case for subsequent investments. This logic establishes the foundation for the next points, which analyze how optimization of berth geometry, depth strategy, and breakwater design contributes to measurable performance improvements.

2. Berth and Terminal Geometry Optimization as a Driver Of Turnaround-Time Reduction

Across the reviewed literature, berth geometry and terminal layout repeatedly emerge as high-leverage determinants of turnaround time and service stability. Even moderate changes to effective berth length, segmentation, and operational zoning can reduce conflicts and stabilize berth windows under variable arrival patterns. In many regional ports, the operational consequence of limited berth flexibility is that a single vessel can block others, generating queueing spikes that disrupt schedules. Studies emphasize that berth improvements must be assessed together with yard and gate flows, because increased berth productivity can quickly shift congestion downstream into storage and internal transport. Therefore, berth and layout optimization is best interpreted as an integrated flow redesign from ship-to-yard-to-gate rather than an isolated physical upgrade.

The review shows that implementable berth allocation improves when physical constraints are clarified and standardized through functional zoning and simpler rules. Clear segmentation by vessel type or cargo activity reduces decision complexity and supports more consistent sequencing, particularly in ports handling mixed vessel calls. This consistency can reduce peak congestion and distribute workload more evenly across operational windows. However, the literature also warns that geometry expansion without rule alignment can increase disorder and lead to inefficiencies in the yard. As a result, operational discipline, including berth-window planning and priority rules, is treated as a complementary intervention that protects the benefits of physical optimization.

Terminal layout is repeatedly discussed through the mechanisms of travel distance, interference, and congestion externalities. Shorter equipment travel paths reduce cycle times and raise effective handling rates, while improved separation of internal flows and gate movements reduces conflict and idling. Several studies highlight that congestion effects can dominate performance even at moderate throughput levels, making layout optimization valuable beyond large ports. For Eastern Indonesia, robust and simpler layouts are often recommended due to constraints in staffing, equipment availability, and maintenance capability. The expected benefit is not necessarily maximum productivity but stable productivity with fewer extreme drops during demand fluctuations or operational stress.

Another consistent finding is that berth and yard improvements can yield network benefits by improving synchronization between hubs and feeders. When turnaround time becomes predictable at a hub, feeder services can connect more reliably, reducing missed connections and the need for contingency storage. This reduces dwell time and supports more stable inventory planning for shippers serving remote islands. The literature frames this as a shift from reactive operations toward planned operations, which is essential in archipelagic corridors where slack capacity is expensive and difficult to maintain. Consequently, berth and layout optimization can improve both local port efficiency and corridor-level service reliability.

The review also identifies a frequent gap between optimization results and practical implementation. Some studies report that technically optimal plans fail when they ignore real constraints such as labor windows, mixed cargo patterns, equipment downtime, and limited decision-support tools. In smaller ports, the most effective interventions are often basic but enforceable, such as clear traffic separation, operational zoning, and standardized procedures. This aligns with evidence that minor operational frictions can erase gains from physical upgrades if governance and day-to-day discipline are weak. Therefore, the literature supports a minimum viable modernization approach that couples geometry improvement with practical rules and training to ensure adoptable outcomes.

Table 3. Comparison of berth and layout improvement packages

Package	Primary design focus	Supporting operational change	Main mechanism	Dominant KPI improved
A (Low-cost)	Berth zoning and markings	Basic berth-window discipline	Reduces conflicts	Waiting time
B (Balanced)	Effective berth length improvement	Flow simplification	Faster handling cycles	Turnaround time
C (Capacity)	Berth length and width expansion	Yard reconfiguration	Higher throughput potential	Berth utilization
D (Reliability)	Mooring and fender upgrades	Congestion buffers	Fewer stoppages	Schedule predictability

Source: Author, 2025

In summary, the literature supports berth and terminal layout optimization as a practical first-stage pathway to reduce turnaround time and stabilize service windows. The strongest benefits arise when physical adjustments are combined with operational rule alignment so that increased berth productivity does not produce yard congestion. Nevertheless, gains may plateau if draft limitations or downtime remain the dominant constraints, especially in exposed or shallow ports. This reinforces the integrated design argument: berth optimization must be coordinated with depth and tranquility strategies to achieve corridor-level cost reductions. The next point discusses how basin and channel depth decisions influence vessel economics and unit transport costs.

3. Basin and Channel Depth Strategies as Determinants of Vessel Economics Corridor Costs

The reviewed literature strongly indicates that basin and channel depth constraints shape the economics of vessel deployment and therefore the cost structure of maritime logistics. Draft limitations reduce vessel payload and often force operators to sail underloaded, increasing the cost per ton transported. In corridors with long sailing distances, this inefficiency compounds through fuel consumption and ship-time utilization, elevating freight rates. Channel restrictions and tidal windows add uncertainty that undermines schedule adherence and increases buffer time, further reducing asset utilization. The synthesis therefore treats depth and access reliability as service enablers that can unlock scale efficiency and reduce reliance on multi-step transshipment chains.

A key discussion across sources is that depth must be optimized rather than maximized, because depth is associated with long-term maintenance requirements and environmental trade-offs. Maintenance dredging uncertainty can be a major risk factor, particularly in silt-prone environments where sedimentation can quickly erode navigable depth. If maintenance regimes are weak, theoretical depth upgrades do not translate into reliable operational access, and operators adopt conservative loading practices that reduce the economic benefit. The literature emphasizes lifecycle assessment, comparing capital investment and recurrent dredging costs against expected logistics savings. This perspective positions depth strategy as a reliability assurance problem grounded in maintainability and governance capability.

Another recurring result is that corridor-level planning produces better outcomes than isolated deepening projects. Upgrading a hub while leaving feeders draft-limited can simply shift bottlenecks downstream and reduce net benefits. Conversely, selective deepening at critical choke points can improve system performance across multiple routes by reducing queueing and enabling smoother arrival sequencing. The literature supports identifying where draft restrictions contribute the most to delays, cancellations, or transshipment dependence and prioritizing interventions there. This approach aligns depth decisions with real service patterns, maximizing spillover benefits across the wider port network.

The literature further links access capability to direct-call attractiveness and reduced transshipment dependence. Ports that can reliably accommodate larger vessels may reduce handling steps and shorten lead times, which can lower total logistics cost for essential commodities. However, benefits depend on demand concentration and the ability to consolidate cargo flows, because larger vessel calls require sufficient volume to be economically sustainable. This introduces an institutional dimension, where policy mechanisms that encourage cargo consolidation and predictable scheduling influence the return on depth investments. Thus, depth improvements are most effective when embedded in corridor strategy rather than treated as stand-alone engineering upgrades.

A final depth-related theme concerns operational safety margins and uncertainty management. Variability in sea level, sediment dynamics, and vessel behavior requires adaptive safety buffers to maintain navigational safety and operational reliability. The literature suggests that monitoring and updated bathymetry are essential for sustaining access reliability and for reducing the conservative operating practices that reduce payload. Where monitoring systems are weak, operators often adopt restrictive loading rules that undermine the objective of improving efficiency. Consequently, the synthesis highlights that strengthening dredging governance and monitoring capacity can be as critical as the initial deepening itself.

Overall, the synthesis indicates that depth strategies generate the greatest logistics benefits when they deliver reliable access for economically appropriate vessel classes and reduce transshipment dependence. Yet depth interventions can underperform if berth congestion or downtime remains binding, which again emphasizes the need for integrated design packages. In practice, depth upgrades should be sequenced with berth and tranquility measures based on the dominant constraint at each port. This framing aligns engineering choices with service-level targets and corridor economics, which is essential for Eastern Indonesia's dispersed and volume-limited markets. The next point addresses breakwater and harbor tranquility design as a key lever for reducing downtime and improving schedule reliability.

4. Breakwater and Harbor Tranquility Optimization to Reduce Downtime

The review identifies operational downtime due to wave agitation as a major reliability constraint that reduces effective capacity and amplifies logistics costs. Even when berth length and depth are sufficient, operations may halt under unsafe mooring conditions, creating backlog surges and destabilizing schedules. Downtime is particularly damaging in networks where feeder routes depend on hub synchronization, because disruptions create missed connections and extended dwell time. The literature suggests that downtime is often underestimated when assessments rely only on annual throughput metrics rather than service continuity indicators. For exposed ports in Eastern Indonesia, harbor tranquility is therefore treated as a core efficiency variable that determines how much capacity is actually usable across seasons.

A consistent discussion across sources is that breakwater design must be tailored to local wave climate, bathymetry, and sediment processes. Generic design solutions risk providing insufficient attenuation or creating unfavorable reflection patterns that degrade operability at berths. Some studies highlight that partial protection may reduce extreme conditions but still allow frequent moderate agitation that causes repeated stoppages. As a result, design evaluation must incorporate operability thresholds, linking wave conditions to mooring safety and allowable handling operations. This approach frames breakwater planning as a service-level design problem focused on reducing downtime frequency and duration.

The literature also emphasizes the trade-off between improved tranquility and navigational access quality. Certain layouts may enhance protection but complicate maneuvering space, turning basin requirements, or channel alignment, thereby shifting constraints from downtime to access congestion. This risk is heightened for ports handling mixed vessel classes with different maneuvering envelopes. Therefore, studies recommend integrated modeling and joint decision-making where breakwater layout is evaluated together with channel geometry and berth arrangement. In this sense, protection infrastructure is not a separate element but part of the port's navigation-operability system.

Another result highlighted in the review is the corridor-level benefit of downtime reduction. When a hub reduces downtime, feeder connections become more reliable, reducing dwell time and storage surges that are difficult to manage in land-constrained ports. For remote islands, fewer cancellations and delays can reduce the risk of stockouts and stabilize prices of essential goods. The literature thus links harbor tranquility to economic resilience, indicating that reliability improvements can yield broader welfare benefits beyond port boundaries. This expands the justification of breakwater optimization from engineering safety alone to logistics stability and regional development impact.

Table 4. Downtime Exposure Levels and Recommended Response Sets

Exposure level	Typical downtime trigger	Operational consequence	Preferred intervention mix	Expected reliability improvement
High	Unsafe mooring and berth agitation	Multi-day backlog	Breakwater + tranquility targets	High
Medium	Intermittent agitation	Schedule drift	Partial protection + mooring upgrades	Medium
Low	Rare agitation events	Minor delays	SOP and mooring management	Low–medium

Exposure level	Typical downtime trigger	Operational consequence	Preferred intervention mix	Expected reliability improvement
Seasonal-high	Clustered seasonal storms	Corridor disruptions	Adaptive operations + targeted protection	Medium–high

Source: Author, 2025

The review also notes that breakwater projects are capital intensive and therefore require rigorous prioritization and staging. Evidence suggests targeting major structural investments only where downtime is frequent enough to dominate total logistics losses. In lower-exposure locations, cost-effective alternatives such as mooring upgrades, operational restrictions, and improved forecasting may deliver better returns. Maintenance and inspection are also identified as critical determinants of long-run tranquility performance because armor stability and structural integrity directly affect protection effectiveness. Consequently, the literature supports aligning breakwater choices with an explicit maintenance strategy to prevent performance erosion over the asset lifecycle.

In summary, harbor tranquility optimization is essential for ports where weather conditions structurally limit reliability and effective capacity. Its performance should be measured through downtime and predictability metrics, ensuring that engineering designs translate into logistics outcomes. However, tranquility improvements must be integrated with depth and berth decisions to avoid shifting constraints and to maximize corridor-level benefits. In Eastern Indonesia, the most robust solutions combine targeted protection, enforceable operational rules, and monitoring routines to stabilize service continuity. The final point integrates these components into a phased implementation logic that emphasizes binding constraints, governance readiness, and measurable service-level improvement.

CONCLUSION

Integrated port-infrastructure optimization is a practical pathway to reduce maritime logistics costs and strengthen inter-island connectivity in Eastern Indonesia, where inefficiencies are often rooted in a mismatch between port roles, physical capability, and operating conditions. The evidence synthesized in the article shows that improving performance requires a system perspective treating berth geometry, navigational access, and harbor protection as linked design choices rather than separate projects. The review highlights three technical levers with direct operational impacts: (1) modern-ship-compatible berth design to reduce berth conflicts and raise handling productivity, (2) optimized basin depth to enable larger drafts and more reliable access, and (3) site-adapted breakwater planning to improve operability and reduce weather-related downtime each influencing key efficiency indicators such as turnaround time, throughput, unit transport cost, and schedule reliability.

Overall, the main implication is that corridor-level efficiency gains will be strongest when ports prioritize integrated, fit-for-purpose interventions aligned with measurable service targets (reliability, access, and turnaround time), supported by governance and operational rules that ensure infrastructure benefits translate into daily performance. Therefore, the article recommends targeted infrastructure investment, adoption of relevant international design standards tailored to local conditions, and strengthened digital port management to improve coordination and performance transparency across the network.

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